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Review

Flame Retardant Polymer Composite and Recent Inclusion of Magnesium Hydroxide Filler Material: A Bibliometric Analysis towards Further Study Scope

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Abstract: Fire accidents occur frequently and pose a great threat to high-rise buildings with flammable construction materials. Recently, researchers have been doing significant work on this topic to improve the flame retardancy of composites by adding inorganic metal hydroxide, such as magnesium hydroxide (MH), due to its higher thermal decomposition temperature and low toxicity. Research on flame retardant polymer composites with magnesium hydroxide is rapidly moving toward a more sustainable and safer future. This article provides a comprehensive review of the research trend along with the most cited publications. Most cited articles were chosen to observe the developments. The data collected from the Scopus database in the second week of March 2023 were also categorised to present country-wise improvement, the subject areas involved, and the author's contribution to the topic. Some issues and challenges have also been highlighted from the analysis. By observing the research direction and highly cited articles, some of the further study scopes are also pointed out to develop fire-rated polymer composites for use as sustainable cladding materials for high-rise buildings.

Keywords: flame retardancy; polymer composites; fillers; magnesium hydroxide; fire; thermal properties; cladding

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1. Introduction

Recently, fire accidents are frequently occurring all around the world, involving losses of human lives and property [1,2]. Globally, three hundred thousand people die annually due to fire burns [2]. According to the Australian Bureau of Statistics Data, 13,002 structural fire incidents in buildings occurred in Australia in 2019, which raises concerns about building fire safety. Most fires have occurred due to combustible polymer composite materials used in buildings [3]. Polymer composite is considered one of the best building construction materials for its versatility, low density, good mechanical properties [4], and cost efficiency [5]. However, one of the drawbacks of polymer composites is their poor flame retardant properties [3]. Flame retardancy of a material refers to the science of slowing the pyrolysis and combustion of combustible material. Different techniques and mechanisms have been developed and used to improve the flame retardancy of polymer composites, such as modifying the constituents in the matrix [2,6–8], adding flame retardant fillers [2,9,10], or providing fire resistance coating around the composites [11].

Different types of flame retardant chemicals and their working principles, listed in Table 1, are used by researchers [2,6–11] to improve the fire performance of polymer composites. For example, halogenated flame retardants were used before as fillers due to their different modes of flame retardancy, both in gas and condensed phases [9,10]. However, recently, various hazard substances regulatory organisations such as RoHS (Restriction of Hazardous Substances in Electrical and Electronic Equipment) and REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) restricted the use of these materials as flame retardants due to the toxic degradation of these products [9]. Therefore, it is suggested to use environmentally-friendly flame retardant building materials, which will reduce the fire death rate and fire spread in buildings.

Table 1. Different types of flame retardant chemicals and their working principle.

Flame Retardant Chemical Nature	Example of Flame Retardants	Working Mechanism	Ref.
Metal oxides and hydroxide	Aluminium hydroxide, Alumina trihydrate, Magnesium hydroxide, Calcium carbonate	Heat sink	[2]
Boron based	Boric acid, Zinc borate, borax, boron phosphate	By forming insulating layer	[12]
Halogen based	TCPA, TBPA, Polybrominated diphenyl ethers, Polybrominated diphenyl	Gas phase	[13]
Phosphorus based	THPC	Condense phase	[14]
Synergistic	Halogen/Antimony trioxide, P/halogen	Flame retardancy of the primary compound enhanced by the presence of another	[15]
Intumescent	Acid donor (ex-ammonium polyphosphate), carbonising agent (ex-pentaerythritol), bowling agent (ex-urea, melamine)	Both in gas and condense phase	[16]

Notes: TCPA = Tetrachlorophthalic anhydride, TBPA = Tetrabromophthalic anhydride, THPC = Tetrakis(hydroxymethyl) phosphonium chloride.

Several research works have been conducted by researchers [2,6–11] on creating flame retardant materials by incorporating flame retardant filler materials. The addition of flame retardant fillers to the polymer matrix has become a common practice and is widely used inorganic flame retardant materials such as halogen, aluminium hydroxide, and magnesium hydroxide [2]. However, the toxicity of some flame retardant fillers, such as halogen, is the key issue [17–20]. Aluminium hydroxide and magnesium hydroxide are the most popular among those inorganic flame retardants [2] due to lower toxicity and better flame retardant properties. Magnesium hydroxide has recently gained more popularity among researchers due to its low toxicity, good thermal stability, higher thermal degradation temperature, and high heat absorption capacity compared to other inorganic flame retardants.

In the last few years, several bibliometric analyses have been conducted on the topic of polymer composites, such as geopolymer composite [21], reinforced polymer composite [22], polymer storage in energy storage systems [23], flame retardant polyurethane [24], flame retardant-induced adverse health effects on human health [25], research on flame retardants for fire safety [26], brominated flame retardants [27], fire resilient underground construction materials [28], and nano-flame retardant materials [29]. However, no bibliometric analysis is found on the flame retardant polymer composites with magnesium hydroxide; however, recently, significant research has been carried out on magnesium hydroxide as flame retardant fillers to improve the fire performance of polymer composites. A bibliometric study is conducted in this study to address the above research gap, which will (1) provide a clear view of the research trend in flame retardant polymer composites with magnesium hydroxide as filler, (2) figure out which countries and researchers are doing tremendous work on this topic, (3) provide detailed information about the most cited articles in this topic, and (4) figure out potential research directions in the flame retardant polymer composites with magnesium hydroxide. This study uses the Scopus database to conduct the bibliometric analysis.

2. Surveying Methodology

2.1. Research Articles Selection Criteria and Process

The surveying approach used in this study for article selection and processing is illustrated in Figure 1. Four steps are used for research article selection and processing from the Scopus database. In the first step, two key topics (Topic 1-'Magnesium hydroxide filler', Topic 2-'Flame retardant polymer composite') are used to obtain all the relevant published documents. The first screening is carried out in the second step to limit the specific document type on each topic and to identify the relevant articles.

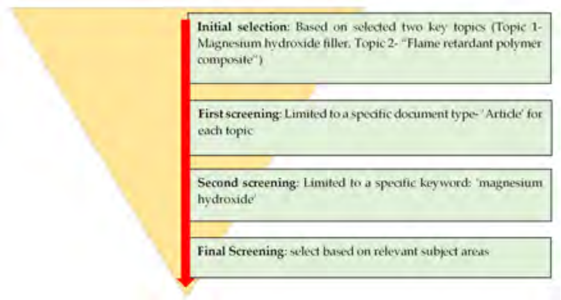


Figure 1. Schematic diagram of article selection criteria and process.

The second screening is also performed in the third step based on the keyword of "Magnesium hydroxide". The last screening is executed in step four based on the relevant subject areas: Material science, engineering, chemistry, chemical engineering, and energy. Finally, only articles relevant to the related subject areas are selected.

The details of the article selection step to identify the documents, using the Scopus database, based on the selection criteria are visually illustrated in Figure 2. In the initial step, 460 and 2457 document were identified in the Scopus database for Topics 1 and 2, respectively. In the following steps, the screening process is conducted by using three criteria, which are document type (article), keyword (magnesium hydroxide) and specific subject areas (material science, engineering, chemistry, chemical engineering, and energy). Based on the screening steps, 157 and 108 articles were finally selected on Topics 1 and 2, respectively, for detailed analysis in this study.

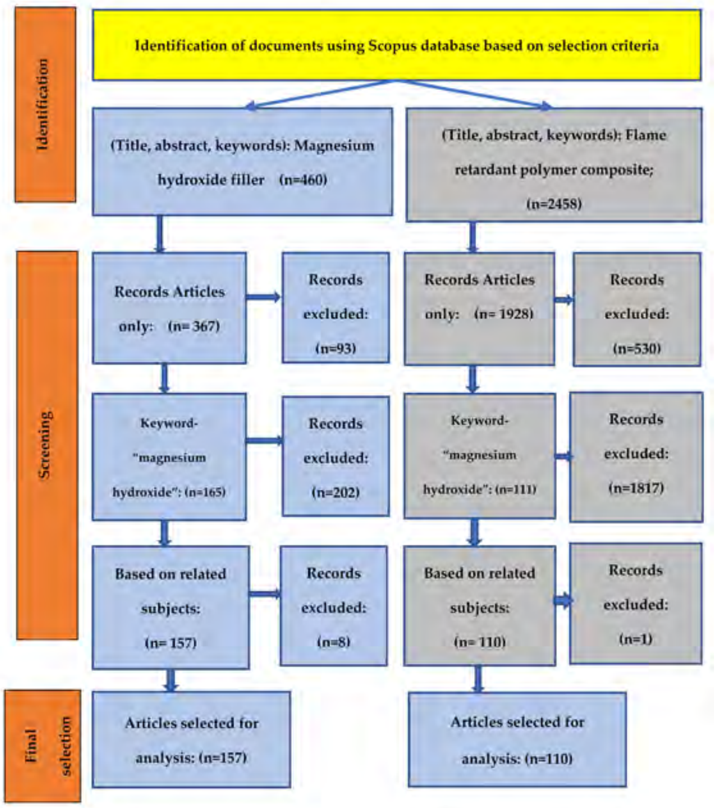


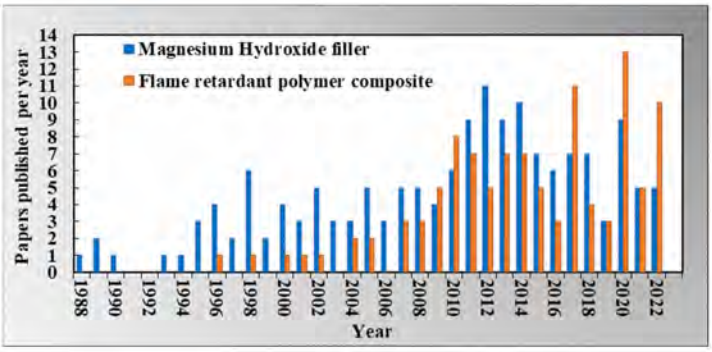
Figure 2. Flowchart diagram for documents selection steps.

2.2. Research Data Extraction and Characteristics

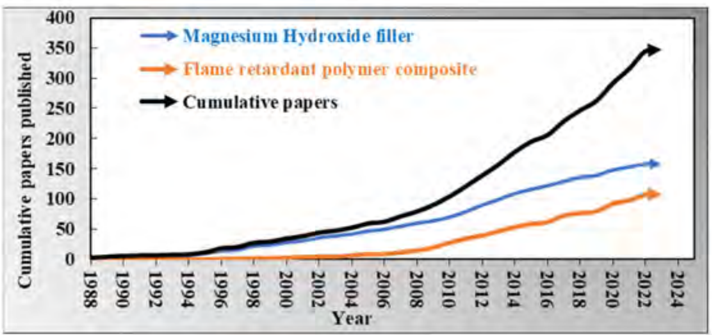
Data extraction and characteristics in the topic of flame retardant polymer composites have been carried out based on eight parameters, such as (1) highest citation in the topic, (2) number of articles published yearly, (3) author name, (4) related subject area, (5) most used keywords, (6) publisher name, (7) country of publication, and (8) source title. The extracted data of the topics mentioned earlier have been analysed to illustrate the research trend and to find out current issues and challenges.

3. Discussion

For a better understanding of the research trend of each topic, the research articles are categorised according to the different parameters mentioned in Section 2.2. The research trends of "Magnesium hydroxide filler" (Topic 1) and "Flame retardant polymer composite" (Topic 2) are illustrated in Figure 3. The paper published each year is presented in Figure 3a and the cumulative papers published until now are shown in Figure 3b. A total of 348 articles were published based on these two topics (157 articles for Topic 1 and 109 articles for Topic 2). The first article published on "Magnesium hydroxide filler" was in 1988, and the trend almost remained the same in the last decade, although there was little decrease in the last two years. Several works have been conducted on "Flame retardant polymer composite" since 1996. In the last two decades, the trend significantly changed. The highest number of research articles was published in 2020 (13 articles), then in 2017 (11 articles), with 10 articles published in 2022 (Figure 3a). The research trend of both topics is upward (see Figure 3b), which clearly indicates that magnesium hydroxide has great potential to develop flame retardant polymer composite materials, due to its diverse properties, including high endothermic decomposition temperature, low cost [30], smoke suppressibility, and non-toxicity [31]. It can be seen from Figure 3b that the cumulative papers number has significantly increased since 2010, which clearly indicates the potentiality of these two topics.



(a)



(b)

Figure 3. Graphical representation of (**a**) paper published per year and (**b**) cumulative papers published on Topic 1 and Topic 2.

3.1. Topic 1-Magnesium Hydroxide Filler

3.1.1. Country-Wise Publication on Topic 1—"Magnesium Hydroxide Filler"

During the survey of Topic 1—"Magnesium hydroxide filler", a total of 157 articles were selected, which were published by 38 countries (based on the affiliation of all authors mentioned in 157 articles). The analysis shows that at least two or more research articles were published based on "Magnesium hydroxide filler" from 25 countries, as shown in Figure 4. It can be noticed that China is the most advanced country in the research on "Magnesium hydroxide filler" and published 41 articles. The United Kingdom (UK) is the second country, which published 36 articles. Almost 50 percent of the 157 articles were published by researchers from China and the UK. Other countries also conduct research frequently, for instance, Malaysia, Italy, Japan, the United States, France, and the Republic of Korea. The connectivity of the co-authored countries is illustrated in Figure 5. It is evident that there is strong collaboration among some specific countries, which are: the United Kingdom, China, Malaysia, the United States, Turkey, and India, and, as a consequence, the publication rate from these countries is also higher in Topic 1.

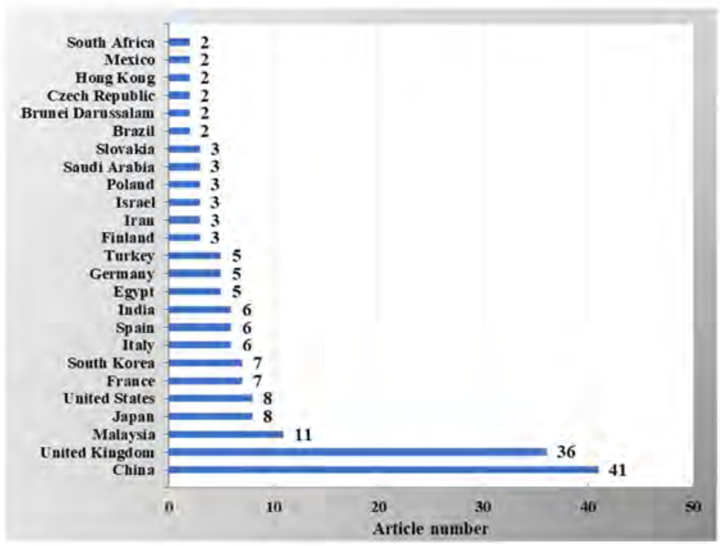


Figure 4. Country-wise number of article publications on Topic 1—magnesium hydroxide filler (minimum 2 publications).

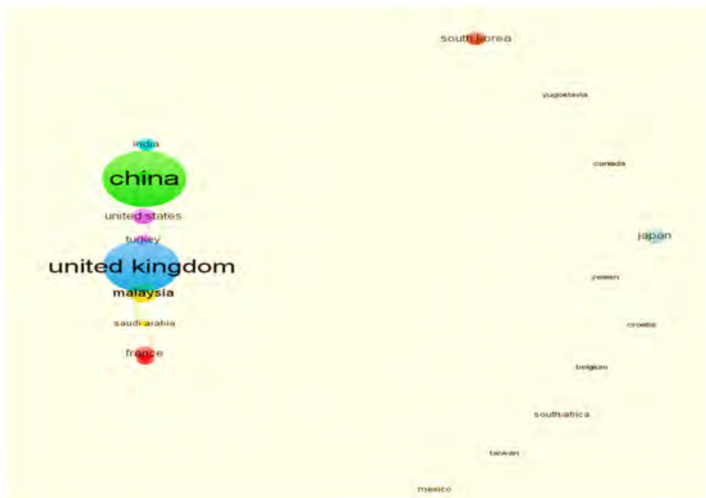


Figure 5. Science mapping of co-authored countries in Topic 1.

The network connectivity of the authors based on the articles published by 38 countries is presented in Figure 6. It is clear from the network connectivity of the authors that there is a significant contribution on this topic from the different individual groups, although there is no strong collaboration between most of the authors except a few groups. The top ten authors who have published articles on the topic of "Magnesium hydroxide filler" are listed in Table 2 based on their publication numbers, including their citation numbers, h-index, and country of origin extracted from the Scopus database. Liauw published 13 articles, which is the highest among the others. He has focused on polypropylene, EVA, and polystyrene composites. He has several collaborative publications with Roger Norman Rothon on magnesium hydroxide filled composites. The effects of surface modification and interfacial modification on a polymer matrix were studied. Hornsby and Rothon each published 11 articles individually. They published most of their articles around 1990. They conducted research on polypropylene, polyamides, and polystyrene composites filled with magnesium hydroxide fillers. Graham Clayton Lees also collaboratively worked with Liauw and Rothon on this topic. He has 10 publications focusing on surface modification and thermal analysis of the composites. J.Z. Liang conducted studies on both magnesium hydroxide and aluminium hydroxide containing composites to improve the thermal properties and flame retardancy of polypropylene composites. Azman Hassan has published 4 articles where he focused on LDPE and polyamides/polypropylene composites. José Ignacio Velasco and Cédlic Morhain both published 4 articles in collaboration, which focused on polypropylene composites with aluminium and magnesium hydroxide.

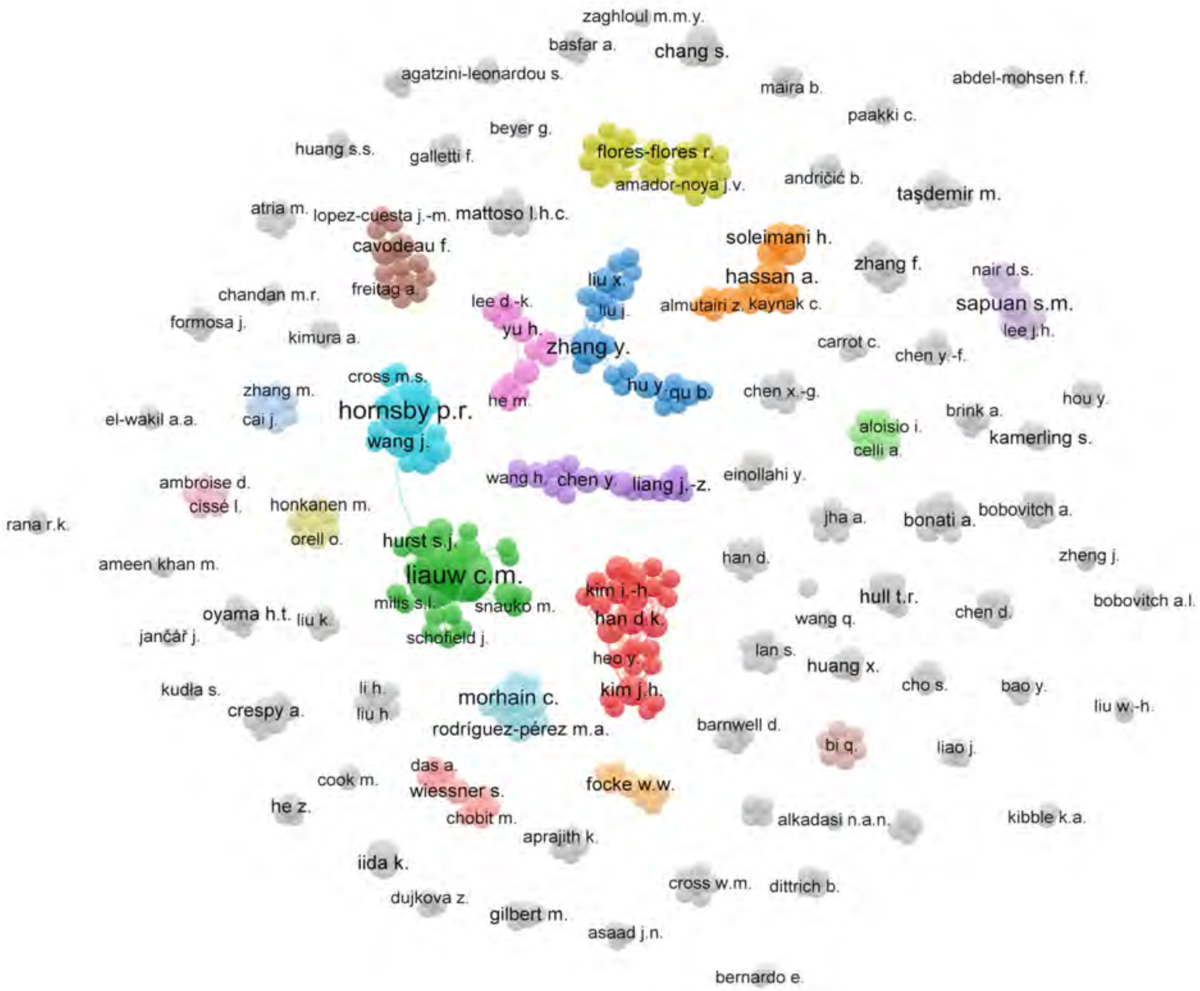


Figure 6. Science mapping of connected authors in Topic 1.

Table 2. Top 10 prolific authors in the topic of "Magnesium hydroxide filler".

Rank	Name	No of Articles	h-Index	No of Total Citations	Country
1	Christopher Mark Liauw	13	27	2715	United Kingdom
2	Peter R. Hornsby	11	35	4337	United Kingdom
4	Roger Norman Rothon	11	17	1101	United Kingdom
3	Graham Clayton Lees	10	14	697	United Kingdom
5	Jizhao Liang	5	36	5243	China
6	S.M. Sapuan	4	83	26,259	Malaysia
7	Azman Hassan	4	50	8663	Malaysia
8	José Ignacio Velasco	4	36	4316	Spain
9	Cédlic Morhain	4	6	155	Spain
10	Suqin Chang	3	10	241	China

3.1.2. Topmost Cited Articles in "Magnesium Hydroxide Filler"

The topmost cited articles published based on "Magnesium hydroxide filler" are analysed in this section and summarised. The top 50 most-cited articles are shown in Table 3, which includes the author's name, publishing year, number of citations, and publisher name. The most cited article (296 citations) was published in 1996 by Rothon [30]. This article studied the suitability of magnesium hydroxide as a filler with different polymers, such as ethylene vinyl acetate (EVA), polypropylene, and polyamides. The second most cited article (248 citations) was published in 2011 by Hull [31]. It can be seen from the citation of this article that Topic 1 has been receiving more attention from researchers. This article discussed the effects of various mineral fillers such as aluminium hydroxide, calcium hydroxide, hydromagnesite, huntite, ultracarb, and boehmite, as well as magnesium hydroxide. This work also discussed how those minerals physically contributed to the fire-retardant effect [31]. The third most cited article (182 citations) was published in 2004 [32]. The research on this article was conducted based on EVA and magnesium hydroxide blends with fumed silica. Synergistic mechanisms and flammability characteristics were investigated [32]. It noticed that most cited articles were published in the *Polymer Degradation and Stability* journal. It can be seen from Table 3 that 25 out of the 50 most cited articles were published from 2010 to March 2023, which significantly indicates the upward research trend on the "Magnesium hydroxide filler" topic.

Table 3. Topmost cited 50 articles in 'Magnesium hydroxide filler' topic.

Rank	Authors	Year	Cited by	Source Title	Ref.
1	Rothon R.N., Hornsby P.R.	1996	296	*Polymer Degradation and Stability*	[30]
2	Hull T.R., Witkowski A. et al.	2011	248	*Polymer Degradation and Stability*	[31]
3	Fu M., Qu B.	2004	182	*Polymer Degradation and Stability*	[32]
4	Cross M.S., Cusack P.A. et al.	2003	145	*Polymer Degradation and Stability*	[33]
5	Hornsby P.R., Wang J. et al.	1996	128	*Polymer Degradation and Stability*	[34]
6	Dittrich B., Wartig K.-A. et al.	2014	123	*Polymers*	[35]
7	Hornsby P.R., Watson C.L.	1990	114	*Polymer Degradation and Stability*	[36]
8	Wang J., Tung J.F. et al.	1996	101	*Journal of Applied Polymer Science*	[37]
9	Rothon R.N.	1999	98	*Advances in Polymer Science*	[38]
10	Sung G., Kim J.W. et al.	2016	96	*Journal of Industrial and Engineering Chemistry*	[39]
11	Hornsby P.R., Watson C.L.	1989	84	*Plastics and Rubber Processing and Applications*	[40]
12	Liang J., Zhang Y.	2010	70	*Polymer International*	[41]

Table 3. *Cont.*

Rank	Authors	Year	Cited by	Source Title	Ref.
13	Saba N., Alothman O.Y. et al.	2019	68	*Construction and Building Materials*	[42]
14	Hornsby P.R., Watson C.L.	1995	68	*Journal of Materials Science*	[43]
15	Balakrishnan H., Hassan A. et al.	2012	66	*Polymer Degradation and Stability*	[44]
16	Zaghloul M.M.Y., Zaghloul M.M.Y.	2017	63	*Journal of Reinforced Plastics and Composites*	[17]
17	Montezin F., Lopez Cuesta J.-M. et al.	1997	63	*Fire and Materials*	[45]
18	Lu Y., Wu C., Xu S.	2018	61	*Composites Part A: Applied Science and Manufacturing*	[18]
19	Liauw C.M., Lees G.C. et al.	1998	61	*Composites Part A: Applied Science and Manufacturing*	[46]
20	Xu T., Huang X., Zhao Y.	2011	59	*Fire Safety Journal*	[47]
21	Yeh J.T., Yang H.M. et al.	1995	59	*Polymer Degradation and Stability*	[48]
22	Bonati A., Merusi F. et al.	2012	52	*Construction and Building Materials*	[49]
23	Witkowski A., Stec A.A. et al.	2012	51	*Polymer Degradation and Stability*	[50]
24	Zhang Y., Hu Y et al.	2008	50	*Polymers for Advanced Technologies*	[51]
25	Lv J.-P., Liu W.-H.	2007	47	*Journal of Applied Polymer Science*	[52]
26	Velasco J.I., Morhain C. et al.	2002	46	*Polymer*	[53]
27	Chang S., Xie T. et al.	2006	44	*Polymer Degradation and Stability*	[54]
28	Hollingbery L.A., Hull T.R.	2012	43	*Polymer Degradation and Stability*	[55]
29	Ulutan S., Gilbert M.	2000	43	*Journal of Materials Science*	[56]
30	Formosa J., Chimenos J.M. et al.	2011	40	*Thermochimica Acta*	[57]
31	Sonnier R., Viretto A. et al.	2016	39	*Polymer Degradation and Stability*	[58]
32	Shi X., Chen Y. et al.	2014	39	*Bioresource Technology*	[59]
33	Suihkonen R., Nevalainen K. et al.	2012	39	*Journal of Materials Science*	[60]
34	Karidakis T., Agatzini-Leonardou S. et al.	2005	38	*Hydrometallurgy*	[61]
35	Cook M., Harper J.F.	1998	38	*Advances in Polymer Technology*	[62]
36	Chen X., Yu J. et al.	2009	36	*Polymer Composites*	[63]
37	Lee C.H., Sapuan S.M. et al.	2017	35	*Journal of Engineered Fibers and Fabrics*	[64]
38	Moreira F.K.V., De Camargo L.A. et al.	2013	34	*Journal of Agricultural and Food Chemistry*	[65]
39	Moreira F.K.V., Pedro D.C.A. et al.	2013	32	*Carbohydrate Polymers*	[66]
40	Focke W.W., Molefe D. et al.	2009	32	*Journal of Materials Science*	[67]
41	Wang Z., Shen X. et al.	2002	31	*Polymer International*	[68]
42	Klapiszewski Ł., Tomaszewska J. et al.	2017	30	*Polymers*	[69]
43	Jančář J.	1989	29	*Journal of Materials Science*	[70]
44	Oyama H.T., Sekikawa M. et al.	2012	28	*Polymer Degradation and Stability*	[71]
45	Oyama H.T., Sekikawa M. et al.	2011	28	*Journal of Macromolecular Science, Part B: Physics*	[72]
46	He Z., Wekesa M. et al.	2006	28	*Pulp and Paper Canada*	[73]
47	Hornsby P.R., Mthupha A.	1996	28	*Plastics, Rubber and Composites Processing and Applications*	[74]
48	Gwon J.G., Lee S.Y. et al.	2014	27	*Journal of Applied Polymer Science*	[75]
49	Yin J., Zhang Y. et al.	2005	27	*Journal of Applied Polymer Science*	[76]
50	Liauw C.M., Rothon R.N. et al.	2001	27	*Journal of Adhesion Science and Technology*	[77]

The mapping of top journals which have published at least 4 articles related to "Magnesium hydroxide filler" is illustrated in Figure 7. It can be seen that *Polymer Degradation and Stability* and *Journal of Applied Polymer Science* are the most profound journals for publications on Topic 1.

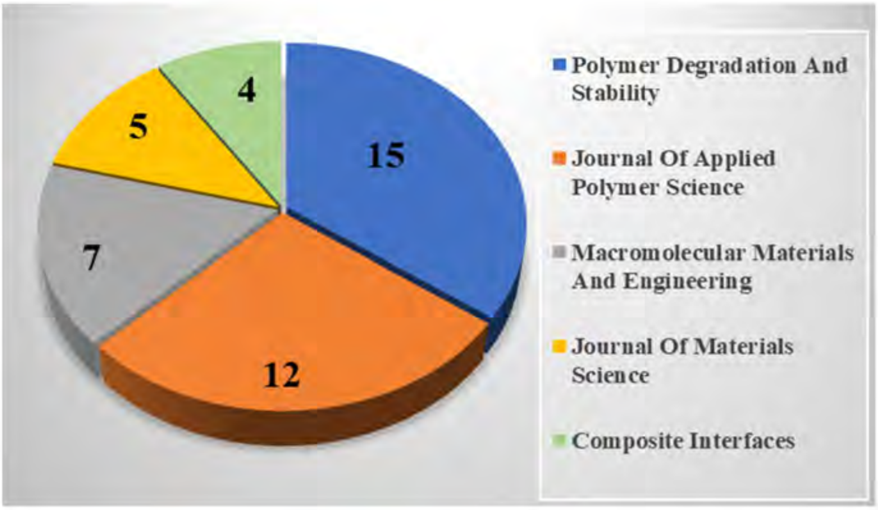


Figure 7. Top journals with a minimum of 4 publications on Topic 1.

3.1.3. Keyword Co-Occurrence

The analysis of keyword co-occurrence among 157 articles extracted from the Scopus database was conducted using CiteSpace software to represent the keyword connective network. There are a total of 11 clusters, and the keywords are illustrated on a time scale as presented in Figure 8. The size of the level and the node size represent the weight of the keyword, while the lines between keywords indicates the links between keywords. By using the keyword cluster function, the information was extracted.

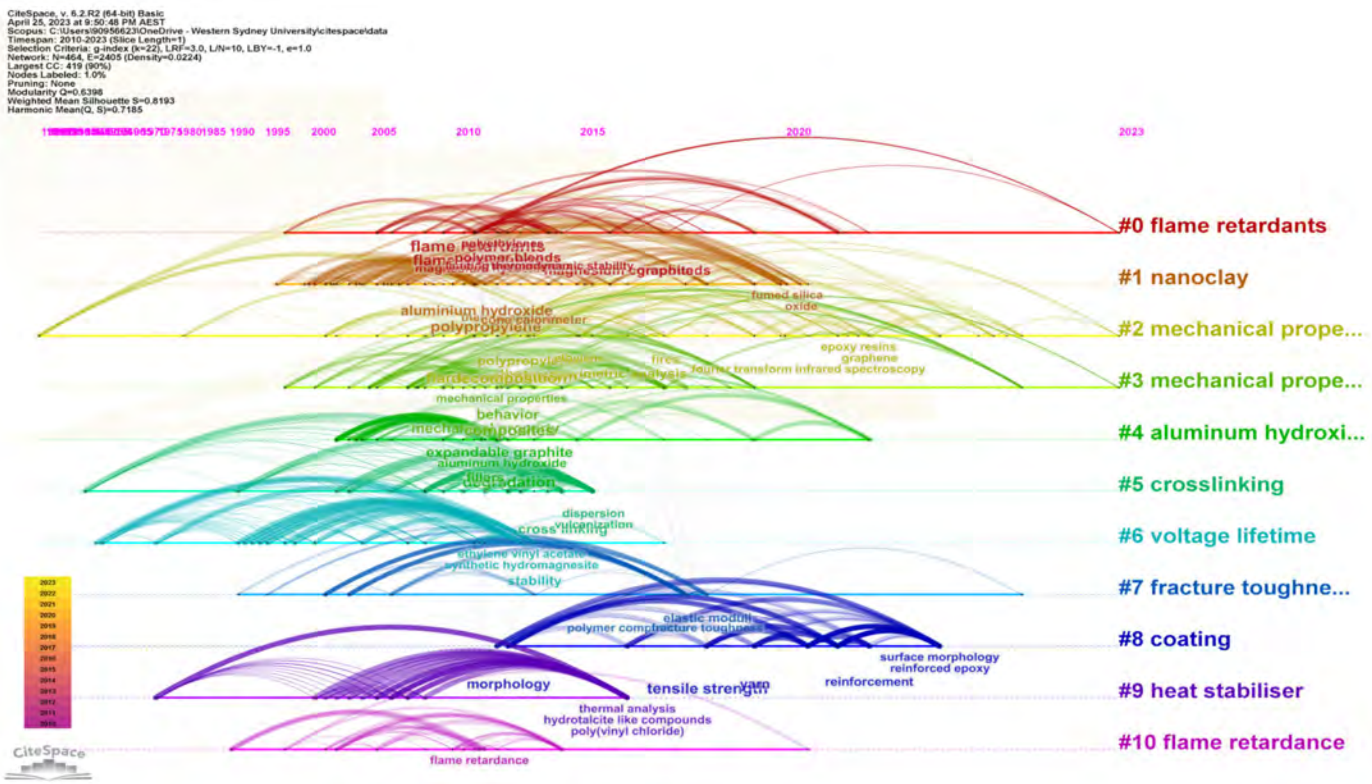


Figure 8. Keyword clusters timeline visualisation for the selected 157 articles of Topic 1 using CiteSpace software.

The keywords are depicted in Figure 8 in form of a time series, showing the research map from 2010 to 2023. The modularity value has been reached at 0.6398, which is greater than 0.3, and implies that the structure is acceptable. The Silhouette scores are also greater than 0.4, indicating the reasonability of the result. The high frequency nodes with high centrality are considered to be the most influential key nodes within the network, which gives detailed information for further analysis. The most cited keywords, along with the year and citation count, have been presented In Table 4 for a better understanding of the research key terms in this topic.

Table 4. Most cited keywords in 'Magnesium hydroxide filler' topic.

SI No	Keyword	Citation Count	Year
1	magnesium hydroxide	195	2010
2	mechanical property	82	2010
3	flame retardancy	69	2010
4	flame retardants	62	2010
5	flame retardant	58	2010
6	Composites	42	2011
7	nanocomposites	42	2010
8	Flammability	41	2010
9	Behavior	39	2010
10	magnesium compounds	32	2015
11	Magnesium	25	2010
12	Degradation	23	2011
13	Polypropylene	21	2010
14	filled polymers	19	2010
15	thermogravimetric analysis	19	2014
16	mechanical properties	18	2011
17	thermal stability	18	2011
18	aluminum hydroxide	16	2010
19	Combustion	16	2010
20	Nanoparticles	16	2015
21	limiting oxygen index	15	2011

All of the details of the 11 clusters are listed in Table 5, showing the top keyword of the clusters and the year it was most cited, which gives a chronological idea of keyword importance. All of the cluster names are (largest to smallest): flame retardants, nanoclay, mechanical properties, mechanical properties, aluminium hydroxide, crosslinking, voltage lifetime, fracture toughness, coating, heat stabiliser, and flame retardance.

Table 5. Cluster by keywords in 'Magnesium hydroxide filler' topic.

Cluster ID	Size	Silhouette	Top Keyword	Year
0	76	0.666	magnesium hydroxide	2012
1	64	0.784	Polypropylene	2008
2	62	0.745	flame retardant	2013
3	58	0.834	mechanical property	2012
4	36	0.816	degradation	2009
5	23	0.993	Cross linking	2005
6	22	0.991	Stability	1997
7	21	0.888	Polymer composite	2012
8	21	0.995	tensile strength	2018
9	18	0.995	Smoke supression	2002
10	18	0.858	Polymers	2006

3.1.4. Subject Area-Wise Document Published

The mapping of the subject areas of 157 articles is also analysed using VOSviewer software and is presented in Figure 9. The subject areas considered in the mapping are materials science, engineering, chemistry, chemical engineering, and energy. Most articles (128 out of 157) were published in material science. Around 9.62% (15 articles) of 157 articles are in the engineering area. Chemistry and chemical engineering have 8.94% (14 articles) of the total publications, whereas only 1.28% of the documents are considered in energy (2 articles).

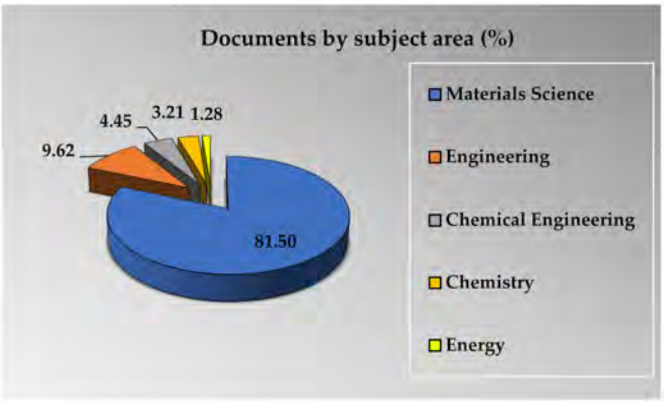


Figure 9. Subject area-wise published articles related to "Magnesium hydroxide fillers".

3.2. Topic 2—'Flame Retardant Polymer Composite'

3.2.1. Country-Wise Publication

The country-wise publication is analysed in this study. It is noticed that there are 29 countries that have published at least 1 or more articles on Topic 2—"Flame retardant polymer composite". Figure 10 shows the list of 20 countries that have published at least 2 articles. Among those, China conducted a lot of research on the flame retardant polymer composite containing magnesium hydroxide as filler material and published 63 articles out of 108 selected articles. The rest of the countries published less than 10 articles. The United Kingdom and the United States also published five and four articles, respectively. The country-wise co-authorship is represented in Figure 11, where it can be noticed that there is no collaborative network cluster except for the cluster of the United Kingdom, China, and the Republic of Korea.

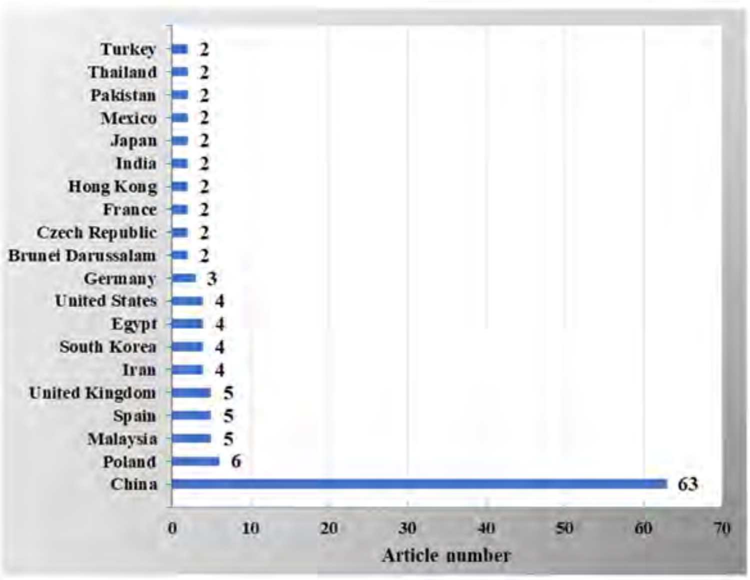


Figure 10. Country-wise number of article publication on topic 2 (minimum 2 publications).

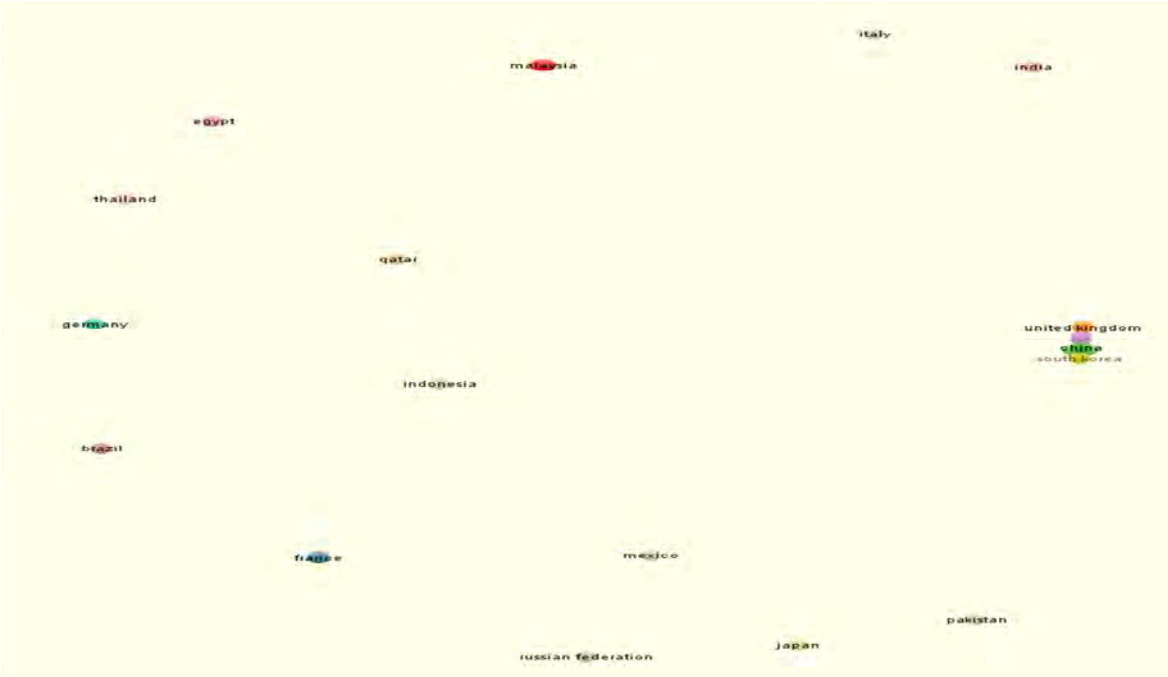


Figure 11. Science mapping of co-authored countries in Topic 2.

The network connectivity of the authors based on the articles published by 20 countries is presented in Figure 12. It is clear from the network connectivity of the authors that there is a significant contribution on this topic from the different author groups. Several authors collaborate with others, as illustrated by different clusters in Figure 12. The top ten authors who have published articles on the topic of "Flame retardant polymer composite" are listed in Table 6 based on the publication numbers, including their citation numbers, h-index, and country of origin extracted from the Scopus database.

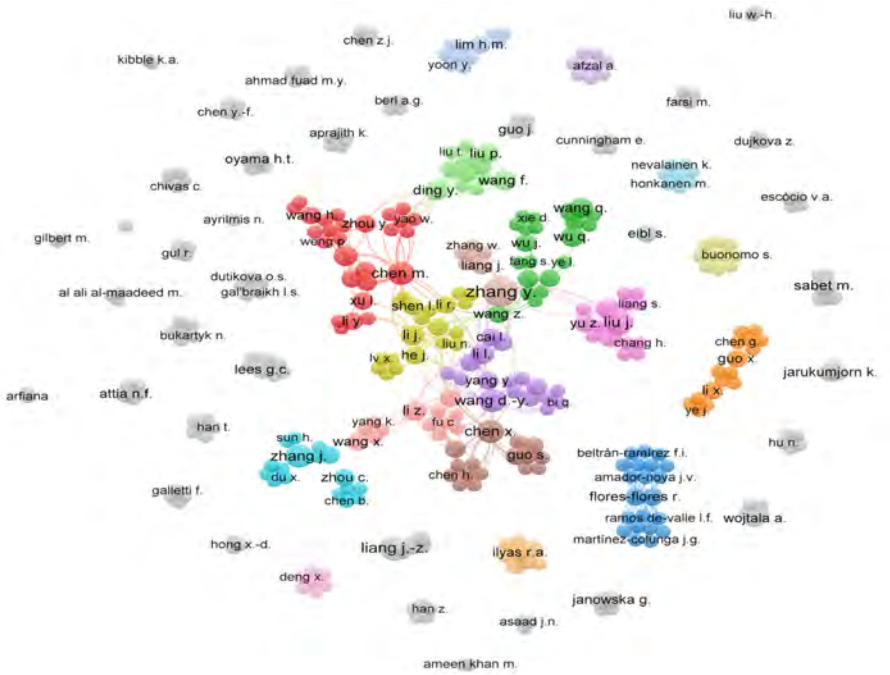


Figure 12. Science mapping of connected authors in the Topic 2.

Table 6. Top authors in the Topic 2—'flame retardant polymer composite'.

Rank	Author Name	No of Articles	h-Index	Total Citations	Country
1	Jizhao Liang	7	36	5242	China
2	Jichun Liu	4	14	588	China
3	Xiaolang Chen	3	22	1789	China
4	Lijuan Li	3	17	845	China
5	Bingli Pan	3	18	1111	China
6	De-yi Wang	3	61	296	Spain
7	Nour F. Attia	2	28	1638	Egypt
8	Liang Cai	2	3	26	China
9	Dehong Chen	2	8	184	China
10	Mingcai Chen	2	24	1839	China

Jizhao Liang published 7 articles on Topic 2. His h-index is 36, whereas the total number of citations is 5242. His highly cited documents are on polypropylene topics. His article on polypropylene composite filled with MH has a total of 30 citations [78]. Jichun Li published four articles, and, among these, three articles were specifically on polystyrene composites. In 2023, he published an article on polypropylene and MH composite where the flame retardancy of the composite was improved by introducing expandable graphite (EG) and microencapsulated red phosphorus (MRP) into the polypropylene/MH composite. Smoke inhibition and acid resistivity of the composite was also improved by the synergistic effect of EG and MRP. The intumescent char layer was formed, which played a key role in modifying the flame retardancy behaviour [79]. Xiaolang Chen also published 3 articles; in one article, which has 20 citations, he studied the flammability and thermal degradation kinetics of polypropylene composites containing EG and MRP [80]. Lijuan Li conducted research on epoxy resin and polypropylene composite. He added functionalised graphene and platelet-like MH to improve the flame retardancy and smoke suppressibility, as well as to reduce toxicity [81]. Bingli Pan has also published three articles. His study on fire performance and thermo-oxidative degradation behaviour of a high-impact polystyrene/MH/MRP composite with an alternating layered structure [32] has been cited 19 times. D.Y. Wang had published three articles focused on EVA/MH and epoxy composites. His study on epoxy composites has 25 citations, which used surface engineered magnesium hydroxide via bioinspired iron-loaded polydopamine [82]. Nour F. Attia, Liang Cai, Dehong Chen, and Mingcai Chen have each published two articles focusing on the modification of magnesium hydroxide. They conducted research on polypropylene and polystyrene composites. In 2015, Attia worked on the flammability of crylonitrile–butadiene styrene nanocomposites, and this study has 26 citations. In this study, magnesium hydroxide nanoparticles were synthesised and modified with organic phosphate [83].

3.2.2. Topmost Cited Articles Information

The topmost cited articles published based on "Flame retardant polymer composite" are also analysed in this section, and the top 50 most cited articles are summarised in Table 7, including the information of author name, publishing year, citation number, and source title. It can be noticed that, on this specific topic, the topmost cited article was published in 2014 by Jeencham, which was cited 38 times. This research work conducted a comparative study of flame retardancy on different flame retardants: Ammonium polyphosphate, zinc borate, magnesium hydroxide, and their combined sample [84]. The polymer matrix was made of sisal fibre and polypropylene. The second most cited article (134 citations) was published by Ye et al. [12]. This study was conducted based on ethylene vinyl acetate/multiwalled carbon nanotube composites, where magnesium hydroxide was added to improve its flame retardant properties. This article aimed to understand the synergistic effect and mechanism of MH with multi-walled carbon nanotubes (MWCN) in an EVA polymer composite [12]. There was another study of sisal fibre and polypropylene matrix, in which magnesium hydroxide and zinc borate were used to evaluate their flame retardant properties [32]. This article has 133 citations. The earliest document on this specific topic was published in 1996 by Wang et al. [37], which has 101 total citations. This article studied the mechanical properties of binary and ternary phase compositions by analysing the microstructure and component interactions [37]. Zhang et al. [51] and Lv et al. [52] both worked on the EVA/MH polymer matrix, where Liang et al. [41] used both MH and ATH as flame retardant additives to a PP composite. Samples made with zinc borate as a flame retardant synergise with the MH/ATH/PP composite, and the effects of this were also studied [41]. Isotactic polypropylene was used with MH to study flame retardancy by Oyama et al. [72]. In the next year, another study conducted by this author, in which, along with Isotactic polypropylene/MH, another flame retardant polymer poly (2,6-dimethyl-1, 4-phenylene ether) (PPE) was added to observe the flammability of the composite [71]. Attia [83] synthesised and wrapped magnesium hydroxide nanoparticles with an organic phosphate shell. The thermal properties of the samples were also studied, and a 71% reduction of the peak heat release rate (pHRR) was achieved.

Table 7. Top 50 articles in 'Flame retardant polymer composite' topic.

SL No	Authors	Year	Cited by	Source Title	Ref.
1	Jeencham R., Suppakarn N. et al.	2014	138	*Composites Part B: Engineering*	[84]
2	Ye L., Wu Q.et al.	2009	134	*Polymer Degradation and Stability*	[12]
3	Suppakarn N., Jarukumjorn K.	2009	133	*Composites Part B: Engineering*	[85]
4	Ghanbari D., Salavati-Niasari M. et al.	2013	110	*Composites Part B: Engineering*	[86]
5	Wang J., Tung J.F. et al.	1996	101	*Journal of Applied Polymer Science*	[37]
6	Liang J., Zhang Y.	2010	70	*Polymer International*	[41]
7	Zaghloul M.M.Y., Zaghloul M.M.Y.	2017	63	*Journal of Reinforced Plastics and Composites*	[17]
8	Zhang Y., Hu Y. et al.	2008	50	*Polymers for Advanced Technologies*	[51]
9	Kim S., Han T. et al.	2017	48	*Electrochimica Acta*	[87]
10	Lv J.-P., Liu W.-H.	2007	47	*Journal of Applied Polymer Science*	[52]
11	Rybiński P., Janowska G.	2013	45	*Thermochimica Acta*	[88]
12	Ulutan S., Gilbert M.	2000	43	*Journal of Materials Science*	[56]
13	Huang N.H., Chen Z.J. et al.	2010	42	*Express Polymer Letters*	[89]
14	Gul R., Islam A. et al.	2011	40	*Journal of Applied Polymer Science*	[90]
15	Sonnier R., Viretto A. et al.	2016	39	*Polymer Degradation and Stability*	[58]
16	Suihkonen R., Nevalainen K. et al.	2012	39	*Journal of Materials Science*	[60]
17	Zadeh K.M., Ponnamma D.et al.	2017	37	*Polymer Testing*	
18	Chen H., Wang T., Wen Y. et al.	2019	36	*Composites Part B: Engineering*	[91]
19	Shen L., Chen Y. et al.	2012	33	*Composites Part A: Applied Science and Manufacturing*	[92]
20	Liu J., Zhang Y.	2011	32	*Polymer Degradation and Stability*	[93]
21	Ferry L., Lopez Cuesta J.M. et al.	2001	32	*Polymer Degradation and Stability*	[94]
22	Wang Z., Shen X. et al.	2002	31	*Polymer International*	[70]
23	Liang J.-Z.	2017	30	*Polymer Testing*	[78]
24	Liu B., Zhang Y., Wan C. et al.	2007	30	*Polymer Bulletin*	[95]
25	Eibl S.	2017	28	*Fire and Materials*	[96]
26	Oyama H.T., Sekikawa M. et al.	2012	28	*Polymer Degradation and Stability*	[71]
27	Oyama H.T., Sekikawa M. et al.	2011	28	*Journal of Macromolecular Science, Part B: Physics*	[72]
28	Suriani M.J., Zainudin H.A. et al.	2021	26	*Polymers*	[97]
29	Attia N.F., Goda E.S. et al.	2015	26	*Materials Chemistry and Physics*	[83]
30	Schofield W.C.E., Hurst S.J. et al.	1998	25	*Composite Interfaces*	[98]
31	Bi Q., Yao D. et al.	2020	24	*Reactive and Functional Polymers*	[32]
32	Suriani M.J., Sapuan S.M. et al.	2021	23	*Textile Research Journal*	[99]
33	Shen L., Shao C. et al.	2019	23	*Polymer Bulletin*	[100]

Table 7. *Cont.*

SL No	Authors	Year	Cited by	Source Title	Ref.
34	Sun L., Wu Q. et al.	2016	21	*RSC Advances*	[101]
35	Ayrilmis N.	2011	21	*BioResources*	[102]
36	Liang J.-Z., Yang J. et al.	2010	21	*Polymer Testing*	[103]
37	Liu P., Guo J.	2007	21	*Journal of Nanoparticle Research*	[104]
38	Liang J.Z., Yang J. et al.	2011	20	*Journal of Applied Polymer Science*	[105]
39	Chen X., Yu J. et al.	2008	20	*Journal of Macromolecular Science, Part A: Pure and Applied Chemistry*	[80]
40	Li Z., Liang W. et al.	2020	19	*Fire and Materials*	[106]
41	Yu Z., Liu J. et al.	2015	19	*Polymer Degradation and Stability*	[81]
42	Rybiński P., Janowska G. et al.	2014	19	*Journal of Thermal Analysis and Calorimetry*	[107]
43	He J., Zeng W. et al.	2020	18	*Journal of Applied Polymer Science*	[108]
44	Weng P., Yin X. et al.	2018	18	*Cellulose*	[109]
45	Chen D., Zheng Q. et al.	2010	18	*Journal of Thermoplastic Composite Materials*	[110]
46	Chen X., Yu J. et al.	2009	18	*Journal of Polymer Research*	[111]
47	Xiao W.-D., Kibble K.A.	2008	18	*Polymers and Polymer Composites*	[112]
48	Liu T., Wang F. et al.	2020	17	*Journal of Applied Polymer Science*	[113]
49	Milis S.L., Lees G.C. et al.	2004	16	*Macromolecular Materials and Engineering*	[114]
50	Liany Y., Tabei A. et al.	2013	14	*Fibers and Polymers*	[115]

The top journals that published at least 4 articles in this topic are shown in Figure 13. It is evident that *Journal of Applied Polymer Science*, *Polymer Degradation and Stability*, and *Fire and Materials* are the profound journals in this topic.

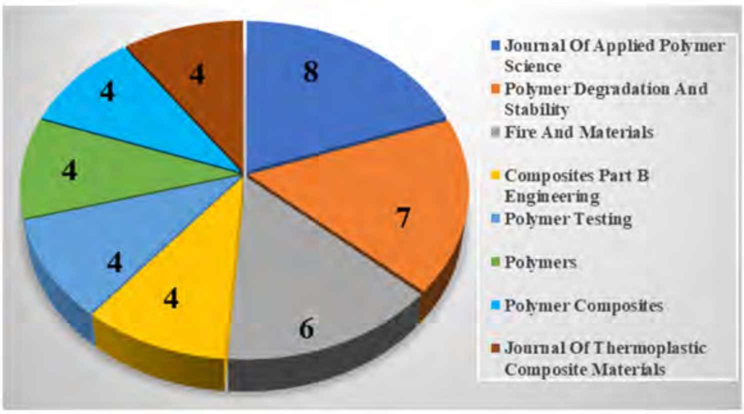


Figure 13. Top journals with minimum 4 publications on the Topic 2.

3.2.3. Keyword Co-Occurrence

The mapping of keyword co-occurrence is analysed for Topic 2. The keywords timeline visualisation is illustrated in Figure 14 from 2010 to 2023. The analysis of keyword co-occurrence among 110 articles extracted from the Scopus database was conducted using CiteSpace software to represent the keywords timeline network. There was also a total of 12 clusters, and the keywords are illustrated similarly as in Section 3.1.3 in Figure 8. The topmost cited (at least 15 citation counts) keywords among the selected 110 articles in Topic 2 are presented in Table 8. Magnesium hydroxide, magnesium compound, and flame retardants are the most cited keywords based on this topic. It is evident that, recently, several filler materials were added in the polymer composite along with magnesium hydroxide. For instance, black carbon, carbon fibres, expandable graphite, carbon nanotubes, and organic natural fibres are getting attention, which can be seen in Figure 14.

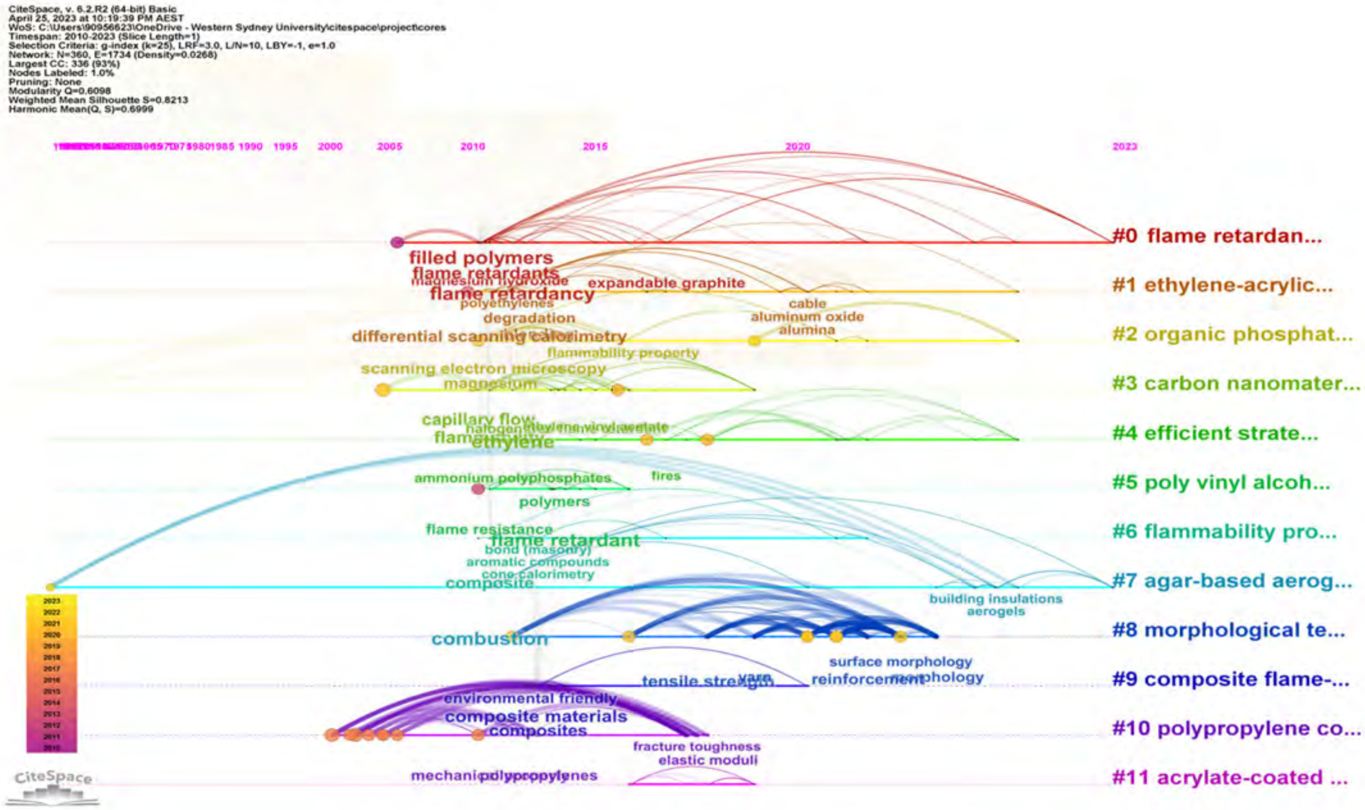


Figure 14. Keyword clusters timeline visualisation for the selected 110 articles of Topic 2 using CiteSpace software.

Table 8. Most cited keywords in 'flame retardant polymer composite' topic.

Sl No	Keyword	Citation Count	Year
1	magnesium hydroxide	90	2010
2	flame retardants	57	2010
3	magnesium compounds	33	2015
4	flame retardancy	26	2011
5	magnesium	23	2010
6	filled polymers	20	2010
7	mechanical property	20	2010
8	flame retardant	18	2013
9	thermogravimetric analysis	15	2014
10	limiting oxygen index	15	2011

The details of all of the 12 clusters are presented in Table 9. The cluster result for this topic is also reasonable, as the modularity value is 0.6098, and the Silhouette score is also much higher than 0.4. Flame retardant composite, ethylene acrylic composite, organic phosphate, carbon nanomaterial, efficient strategy, flower-like magnesium hydroxide nanostructure, flammability properties, agar-based aerogel, morphological tensile, composite flame-retardant material, polypropylene composite, and acrylate coated composite are the clusters presented from largest to smallest in size.

Table 9. Cluster by keywords in 'flame retardant polymer composite' topic.

Cluster ID	Size	Silhouette	Top Keyword	Year
0	57	0.687	magnesium hydroxide	2014
1	51	0.754	Limiting oxygen index	2014
2	34	0.779	magnesium	2015
3	29	0.908	flammability	2014
4	29	0.775	Smoke	2015
5	23	0.831	flame retardant	2013
6	21	0.849	composite	2014
7	20	0.948	combustion	2014
8	19	0.995	Tensile strength	2019
9	19	0.918	composites	2013
10	19	0.94	Mechanical property	2010
11	15	0.944	flame retardant property	2017

3.2.4. Subject Area-Wise Publications

The mapping of the subject areas of the 109 selected articles is also carried out for Topic 2 and presented in Figure 15. The majority of articles (87.26% out of the selected 110 articles) are related to the material science subject, whereas the chemical engineering area includes 8.18% of the documents (9 articles). Both the chemistry and engineering areas contain 2.73% (3 articles) and 0.91% (1 article) of the selected articles, which is reflected in Figure 15. It can be noticed that most of the works are under material science, and some are under chemistry.

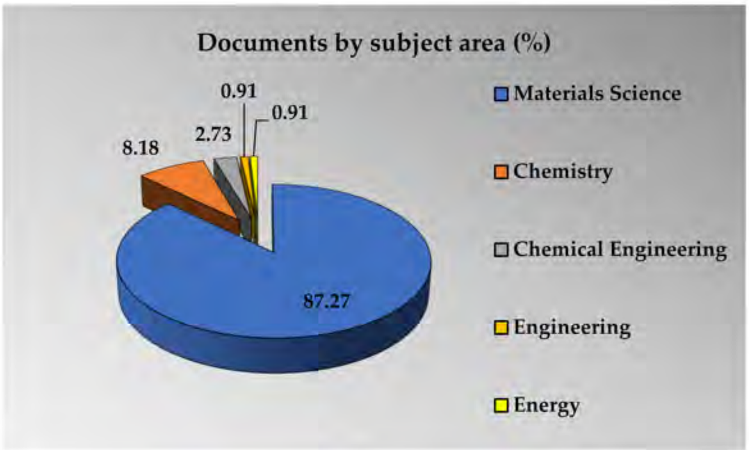


Figure 15. Subject area-wise published articles related to Topic 2.

4. Recent Developments in the Key Topics

After studying the selected articles, it is evident that researchers have been recently trying to make progress on issues such as the higher loading content (approximately 60% MH) [2] requirement of filler materials for better flame retardancy performance. This high content of filler material impedes the mechanical property of the polymer composites, such as low tensile properties and impact strength [116]. Researchers are currently approaching different techniques, such as surface modification of magnesium hydroxide (MH) [7,117,118], particle size of MH [8,119], and synergistic effect of MH [9,33,42,45,94]. Several works have been conducted on the surface modification of magnesium hydroxide to improve the compatibility of MH with the polymer composites by encapsulating elements such as polyphosphazene [120], vinyltriethoxysilane [121], and grafted maleic anhydride [122]. Huang [7] applied the surface modification technique to evaluate the stearic acid surface modification of MH. It was confirmed that, with this surface modification technique, the flame retardancy and rheological property, as well as the mechanical properties of the composites, were improved. The LOI value of the composites decreased by 4 in the case of 7 to 15% stearic acid coating content. The tensile strength of the composites decreased with the increase in stearic acid coating content up to 15 wt%, while the elongation at break was increased by up to 500%.

Particle size also has a greater impact on the flame retardant behaviour of composites [123]. Recently, different synthesis methods have been developed to prepare magnesium hydroxide nanoparticles [124–126]. Huang [8] focused on the particle size of magnesium hydroxide. Four sizes were chosen (2.33 µm, 2.9 µm, 3.89 µm, and 50 nm) to observe the effect of the sizes of magnesium hydroxide particles on the flame retardancy property of ethylene vinyl acetate/magnesium hydroxide polymer composite. It was identified that the flame retardancy property greatly improved with smaller particle size, and it showed the best result in the case of nanoparticles [119]. The improvement depends on the composite preparation procedure, and proper dispersion of the magnesium hydroxide to the polymer matrix is crucial. Researchers also used coated magnesium hydroxide with other fillers in order to improve the flammability properties of the resultant composites [127]. The synergistic effect of magnesium hydroxide with different fillers creates a compact, homogenous char layer that acts as a thermal barrier to prevent heat and oxygen transfer into the composites [2].

After studying the selected articles thoroughly, the topmost 10 polymer composites were identified, listed in Table 10; MH was used as flame retardant filler along with other materials. Among these, polypropylene was most studied polymeric material to prepare flame retardant polymer composite containing MH filler. In addition, EVA, nanocomposites, epoxy resin, and LDPE polymer have also been studied frequently by researchers.

Table 10. Topmost 10 polymer composites studied in the selected articles in the 2 key topics.

Sl No	Polymer Composite	Ref.
1	Polypropylenes	[12,13,16,36,37,41,43–46,54,62–64,70–72,74–76,78–80,84,92,94,101,103,105,110–112,117,122,127]
2	Ethylene vinyl acetate copolymer	[7,8,33,51–53,58,89,98,100,113,114,120,123]
3	Nanocomposites	[65,66,83,85,113,124–126,128]
4	Epoxy resins	[32,42,60,81,96,97,99]
5	Low density polyethylene (LDPE)	[10,11,20,49,68,90,93]
6	Rubber	[88,106,107,121]
7	High density polyethylene (HDPE)	[17,56,115]
8	Polystyrenes	[55,82,104]
9	Polyvinyl chlorides	[18,46,69]
10	Polyamide	[34,44,118]

5. Current Challenges

Although researchers have developed different flame retardant polymer composites with magnesium hydroxide filler, there are still some challenges that exist at present which need to be addressed.

1. Efficiency: The content of magnesium hydroxide filler in polymer composite is crucial for the optimum mechanical properties. As the high content of magnesium hydroxide greatly affects the mechanical properties of the polymer composite, such as tensile strength, impact strength, and Young's modulus, it is still a challenge to keep the content of magnesium hydroxide below 15% [2]. It would be highly desirable to lower the content of magnesium hydroxide to improve the mechanical properties.
2. Preparation methods of magnesium hydroxide for controlling crystal size: Several synthesis routes of magnesium hydroxide have been developed by researchers [23,25,27]. However, for controlling the crystal size of magnesium hydroxide particles, researchers are challenged to propose more synthesis routes for magnesium hydroxide particles. The crystal size has a great impact on the mechanical and flame retardancy properties of polymer composite [2].

3. Sustainability: Several biopolymers are used to prepare polymer composites for sustainable and eco-friendly composite materials instead of plastic [129]. Only a few studies were conducted on biopolymer composites containing magnesium hydroxide filler [128]. Maintaining good mechanical properties with better flame retardancy while also developing sustainable and eco-friendly composite materials will be a crucial challenge for researchers.

6. Conclusions and Further Study Scope

This research summarised the present state-of-the-art in flame retardant polymer composites with the inclusion of magnesium hydroxide as filler material. The published articles were analysed based on the country-wise publications, topmost cited articles, keyword co-occurrences, subject areas, and most prolific authors on the topics discussed. The research trends, issues, and challenges on flame retardant polymer composites with magnesium hydroxide were also highlighted and recommended for future research study. Based on this research, the following conclusions can be drawn:

- It was observed that the research trend was clearly upward, especially in the last few years. Researchers have conducted numerous works in order to improve the flame retardancy of polymer composites. The use of magnesium hydroxide as filler in polymer composite has been increasing due to its potential flame retardant properties over other inorganic metal hydroxides.
- Several countries pay attention to improving the flame retardant properties of polymer composite using magnesium hydroxide. However, the research conducted in China compared to other countries is more noticeable and there are more published articles. It is noticed that several approaches have been proposed that remarkably improved the flame retardant properties of the polymer composites.
- Though magnesium hydroxide has higher thermal stability and low toxicity, there is a reduction in mechanical properties when a high content of magnesium hydroxide is used. Different approaches, such as surface modification, synthesis procedure for magnesium hydroxide fabrication, adding 26ompatibilizer, and synergy formation between magnesium hydroxide and other fillers can be used to overcome this issue.
- Different types of fibres, including biopolymer fibres, are also used with magnesium hydroxide in many composites, which greatly improved the flame retardancy and mechanical properties of polymer composites. However, the dispersion of biopolymer fibres is one of the key issues.
- Further research can be conducted on building cladding core material containing magnesium hydroxide filler, biopolymers, and fibres to investigate the overall impact and suitability in high-rise buildings.

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